The Future of Top Physics at the Tevatron and LHC

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1   Introduction

With the recent discovery of the top quark at Fermilab, [1, 2] top physics has moved from the search phase into the study phase. The very large mass of the top quark separates it from the other fermions and presents the possibility that new physics may be discovered in either its production or its decays.

In this paper I review the prospects for measurements of the top quark production and decay parameters over the course of the next ten years or so.

2   Top Yields

2.1   Tevatron Accelerator Upgrades

With the turn on of the Main Injector at the Tevatron it is predicted that the average instantaneous luminosity will reach 2×10^{32} $cm^{-2}s^{-1}$ with a peak luminosity of 5×10^{32} $cm^{-2}s^{-1}$. Integrated luminosity delivered during Run II, beginning in 1999, is expected to be 2 fb^{-1}. In addition to these luminosity upgrades, the Tevatron will also be undergoing an energy upgrade from $\sqrt{s}$ =1.8 TeV, to $\sqrt{s}$ = 2.0 TeV, which gives an approximate 40% increase in the $t\bar{t}$ production cross section.

2.2 Tevatron Detector Upgrades

CDF and D0 both have significant detector upgrades planned prior to Run II. I here use CDF as an example to calculate $t\bar{t}$ yields, but the numbers for D0 should be similar.

Significant tracking upgrades are planned at CDF including a 3-D silicon tracker and a fiber tracker which will allow stand-alone tracking out to $\mid \eta \mid$=2.0. The efficiency for tagging at least one b-jet in a $t\bar{t}$ event is expected to be 80% and for double tagging close to 40%.

Improvements in lepton identification will come from an upgrade to the end plug calorimeter and through the completion of the muon coverage. The increase in the acceptance for electrons from $t\bar{t}$ decays is expected to be 36% and that for muons 25%.

Including the 40% increase in $\sigma_{t\bar{t}}$, an integrated luminosity of 2 fb^{-1} will yield approximately 1400 *tagged* W plus $\geq$3 jet events and about 140 dilepton events from $t\bar{t}$ decays, per experiment.

2.3 Yields at the LHC

Top physics at the LHC is expected to be done primarily during the early running at relatively low luminosities of $10^{32} - 10^{33}$ $cm^{-2}s^{-1}$. At $\sqrt{s}$=14 TeV and 10^{32} $cm^{-2}s^{-1}$, this corresponds to about 6000 $t\bar{t}$ pairs produced per day. Folding in typical detection efficiencies, one can expect of order 100 tagged lepton + jet events on tape per day and about 20 dilepton events on tape per day. Only searches for the rarest phenomena in top production or decays will be limited by statistics at the LHC.

3 Mass Measurement

3.1 Current Status and Prospects at the Tevatron

The current CDF top mass measurement, from an integrated luminosity of 67 pb^{-1} is $M_{top} = 176 \pm 8 \pm 10$ GeV/c^2, where the first uncertainty is statistical and the second is systematic. One observes that already the statistical and systematic uncertainties are comparable and therefore the future precision will be determined by systematic effects (for Run II the statistical uncertainty will be $\sim$1 GeV/c^2).

Both CDF and D0 use constrained fitting of b-tagged W+$\geq$ 4 jet events, using the four highest E_T jets, to measure the mass. The dominant systematic effects are due to the understanding of the jet energy scale in the detector, the effects of gluon radiation, biases due to b-tagging, and the understanding of the shape of the underlying background. In evaluating how the systematic uncertainties are likely to scale with increased integrated luminosity, the key question is whether a control dataset exists with which to study the effect in question. If so, then it is reasonable to assume that the uncertainty will scale as $1/\sqrt{N}$.

Uncertainties due to jet energy scale and gluon radiation effects are studied using photon-jet balancing and Z + jet events, thus energy scale uncertainties can be expected to scale down as $1/\sqrt{N}$. However, in addition to energy scale uncertainties, the effects of initial and final state radiation create combinatoric confusion. Combinatoric effects can be significantly reduced with increased statistics by such things as requiring both b-jets to be tagged, which reduces the number of possible particle assignments to four, and through the requirement of four and only 4 high E_T jets in the event. It is unclear how uncertainties due to combinatoric effects will scale, but it is clear that they will be significantly reduced with a large increase in dataset size.

Uncertainties due to b-tagging bias are currently understood with control samples of inclusive lepton events and with the $t\bar{t}$ Monte Carlo samples. This uncertainty is not large to begin with and should scale statistically.

The uncertainty due to the background shape is currently studied using the VECBOS Monte Carlo program, which is in turn validated using W+1,2 jet data. With increased dataset size it should be possible to study the background shape using top depleted datasets, selected for instance by *anti*-b tagging, and with Z+$\geq$ 3 jet events. It is conceivable that background shape uncertainties will scale statistically, but uncertain.

If we assume statistical scaling of the systematic uncertainties from the current 67 pb^{-1} values, the uncertainty projected at the completion of Run II will be 2-3 GeV/c^2. Conservatively we can expect < 4 GeV/c^2.

3.2 Prospects at LHC

The subject of top mass fitting at LHC has been studied by several authors. [3, 4, 5] In the lepton plus jets channel, the technique will likely be

quite similar to that now employed at the Tevatron. In the LHC event samples, the statistical uncertainty in the mass fitting will be negligible, and the systematic effects will be similar to those now under study at the Tevatron. With the enormous datasets, however, several new handles for control of the systematics are available. We list below the major systematic effects and the available datasets used to control the uncertainties:

- Jet Energy Scale: With large enough statistics the relevant jet energy scale can be measured directly in $t\bar{t}$ events by renormalization of the reconstructed mass of the hadronically decaying W boson. Indeed, at CDF one is already able to reconstruct a W mass peak on the hadronic side in $t\bar{t}$ events when the W mass constraint is *removed* from the fitting procedure. [6] The difference between the energy scale for jets from the W decay and the energy scale for b-jets will become more important as the uncertainty in the mass measurement decreases. With sufficiently large datasets, the b-jet energy scale can be understood using $Z \rightarrow b\bar{b}$ and $WZ \rightarrow \ell\nu b\bar{b}$ events.

- Gluon Radiation: The LHC will provide copious samples of Z+jet events which provide an excellent sample for measuring the effect of gluon radiation on jet reconstruction. Furthermore, it may be possible to study hard gluon radiation, which can produce additional high P_T jets, in $t\bar{t}$ events themselves by measuring the population of additional jets.

- b-Tagging Bias: This systematic effect is already small at the Tevatron and is expected to be negligible at the LHC.

- Background Shape: There is little work on the effect of the uncertainty in the shape of the underlying background on the top mass fitting at the LHC, but it should be possible to study this directly using carefully constructed 'top-free' datasets.

The LHC literature quotes an overall uncertainty on the top mass measurement from lepton plus jets events of ± 3 GeV/c^2. This work was done prior to the discovery of top at the Tevatron, and given the current experience seems extremely conservative. More likely the final uncertainty at LHC will be in the 1-2 GeV/c^2 range.

4 Measurement of $\sigma_{t\bar{t}}$

The measurement of the production cross section for $t\bar{t}$ pairs is a test of QCD. A significant deviation of the measured cross section from the predicted value can signal non-Standard Model production mechanisms such as the decay of a heavy object into $t\bar{t}$ pairs. As there is relatively little uncertainty in the theoretical prediction for the cross section, [7] this can be a rather sensitive testing ground. The Tevatron and LHC measurements of $\sigma_{t\bar{t}}$ are complementary. Although the LHC at higher $\sqrt{s}$ has greater reach, the dominant glue-glue nature of its collisions makes it insensitive to a spin one color singlet resonance, while there is no such restriction at the Tevatron where high $\sqrt{\hat{s}}$ collisions are dominantly $q\bar{q}$.

The uncertainty in the production cross section at the Tevatron is currently of order 30% and is dominated by statistics. With the statistics of Run II, one can expect a 10% measurement. At this point uncertainties due to acceptance and integrated luminosity become comparable to the statistical uncertainty and it is uncertain how much more precise the measurement can become. In any case, the ultimate precision in the luminosity is 3.5%, which is the accuracy to which the effective cross section of the luminosity monitors is known, so one can expect that the uncertainty in the cross section measurement will plateau in the range 5-10% . The final uncertainty in the LHC measurement is likely to be in the same range.

5 Single Top Production

Single top production can occur through both the W-gluon fusion process, with a t-channel W [8] or through an s-channel W* decay. [9] In either case the final state contains one top and one bottom quark and, in lowest order, nothing else in the case of s-channel W* decay, while the W-gluon fusion process contains an additional light quark jet in the final state. The cross section for single top production is proportional to the square of the CKM element V_{tb} and is therefore of great interest.

5.1 W-gluon Fusion

The signal for single top production is extracted via the Wb invariant mass distribution in b-tagged events. There is a significant background from $q\bar{q} \rightarrow Wb\bar{b}$ and the signal to background at the Tevatron is expected to be only 1:2. With 2 fb^{-1} of Run II data however, the Wb mass peak can be extracted above background and a cross section measurement with a statistical uncertainty of better than 20% is expected. [10] Extraction of V$_{tb}$ from this measured cross section depends on the knowledge of the gluon distribution function and therefore an accuracy of no better than 30% is expected. Comparable S/B and final uncertainty on V$_{tb}$ can be expected at LHC.

5.2 W* →tb

The single top signal in this decay mode is also extracted via the Wb invariant mass distribution, as above. However, the backgrounds from the W-gluon fusion process can be reduced by vetoing events with additional jets and from W$b\bar{b}$ by making an invariant mass cut on the $b\bar{b}$ pair of >110 GeV/c^2 (this cut is more efficient for the W* process than for W-gluon fusion). [9]

This process has a significant advantage over the W-gluon fusion process for measuring V$_{tb}$ because it is not sensitive to the gluon distribution function, and the uncertainties in the quark distributions can be controlled by normalizing to $q\bar{q} \rightarrow \ell\nu$ at the same $\sqrt{\hat{s}}$. With 2 fb^{-1} at the Tevatron, a 12% measurement of V$_{tb}$ is expected.

At LHC the W* signal is swamped by W-gluon fusion and $t\bar{t}$ production, both of which grow faster with $\sqrt{s}$ than the $q\bar{q}$ initiated W* process. It is unlikely therefore, that the measurement of V$_{tb}$ with this technique at LHC will compete with the measurement at the Tevatron.

6   Measurement of V$_{tb}$ from Top Decays

In addition to the single top measurements discussed above, there is also sensitivity to V$_{tb}$ by measuring the branching fraction $t \rightarrow Wb/t \rightarrow Wq$. This branching fraction is currently measured at CDF, via the ratio of $t\bar{t}$ events with 0,1 or 2 b-tagged jets, to about 30%. With 2 fb^{-1} a branching fraction uncertainty of 10% is expected.

Converting the branching fraction measurement to a measurement of V_{tb} requires assumptions about the magnitudes of V_{td} and V_{ts}. Since these latter two CKM elements are quite small in the Standard Model, the branching fraction measurement is not a terribly sensitive way to measure V_{tb}, assuming V_{tb} is close to 1 . A 10% measurement of the branching fraction corresponds to a 1σ lower limit on V_{tb} of 0.26. At LHC, assuming a branching fraction uncertainty of 1%, the lower limit on V_{tb} is only 0.4 .

7 $\quad t \rightarrow H^+ b$

Supersymmetric models include charged Higgs bosons which couple to top quarks with a strength which depends on the Higgs mass and the ratio of vacuum expectation values, $\tan\beta$. The Higgs subsequently decays to $\tau\nu$ or cs. The branching fraction dependence of the top and Higgs decays on $\tan\beta$ is shown in Figure 1.

The ratio, $R_{\ell\ell}$, of the rate of $t\bar{t}$ pairs decaying into dilepton final states to those decaying into single lepton final states is, in principle, sensitive to the presence of a charged Higgs component of the top decays. However, the contributions to both the dilepton and single lepton final states from $H \rightarrow \tau\nu$, cs must first be understood.

Extrapolating from the current Tevatron experience, $R_{\ell\ell}$ will be measured to $\sim 10\%$ with 2 fb^{-1}, where the uncertainty is dominated by the statistics of the dilepton sample. At LHC, the measurement is dominated by uncertainties in the backgrounds, which can be controlled somewhat via b-tagging in both the single lepton and dilepton channels. [3] A measurement of the ratio to less than 5% is a reasonable expectation. In either case, Tevatron or LHC, there is sensitivity to only a limited $\tan\beta$ range for a given Higgs mass (see Fig.1).

A more direct method for searching for charged Higgs decays is to look for an excess of taus in top decays. An LHC study [11] has shown that this technique can be sensitive to a charged Higgs over most of the $\tan\beta$ range if M_{Higgs} is near 150 GeV/c^2.

8   W-t-b Vetex

The most general form of the W-t-b vertex has 4 form factors: F_L^1, F_R^1, F_L^2, and F_R^2. [12] In the Standard Model, only F_L^1, the V-A form factor, is non-zero at lowest order. Experimental sensitivity to the values of these form factors can be achieved by measuring the polarization of the W bosons in top decays. In the Standard Model, the ratio of the number of longitudinally polarized to transversely polarized W bosons depends on M_{top}^2 and gives about 70% longitudinally polarized Ws for M_{top}=175 GeV/c^2. The fraction of longitudinal W bosons can be measured using the angular distribution of leptons from W decays in top events. Non-zero values of $F_{L,R}^2$ would produce a departure from the predicted value. A non-zero F_R^1 gives a V+A component of the coupling but does not affect the fraction of longitudinal W bosons. However, it would produce a right-handed component in the transverse Ws and therefore there is also sensitivity to F_R^1 in the lepton angular distributions.

Studies at the Tevatron have shown that a 2 fb^{-1} sample would give a statistical uncertainty of 3% on the fraction of longitudinal, and a 1% statistical uncertainty on the fraction of right handed, W bosons in top decays. At LHC the statistical uncertainties will be a factor of 3-10 better. In both cases systematic effects, which remain to be studied, are likely to dominate the precision of the measurement.

9   Rare Decays

Flavor changing neutral current decays such as $t \rightarrow \gamma c$ and $t \rightarrow Zc$ are unobservably small in the Standard Model at either the Tevatron or LHC. Any observation of such decays at either machine would be a breakthrough. With 2 fb^{-1} at the Tevatron, branching fraction limits for either of these decays will be at the per cent level, whereas the Standard Model predictions are eight orders of magnitude smaller. The Standard Model prediction for the decay $t \rightarrow Ws$ is of order 10^{-3}, which is about an order of magnitude smaller than the sensitivity at the Tevatron with 2 fb^{-1}. It is possible that LHC will make the first observation of this rare decay.

10   Conclusions

By the turn of the century, Run II at the Tevatron will have produced 2 fb^{-1} of data for both CDF and D0. Each experiment will have measurements of the top mass to better than 4 GeV/c^2, the production cross section to 10%, V$_{tb}$ to 12% as well as searches for rare decay modes of the top. The charged current couplings of the top will have been probed to a few per cent via W polarization measurements. If, as many hope and some expect, the top quark turns out to be a window onto physics beyond the Standard Model, these measurements at the Tevatron may very well yield the first glimpse of that new physics.

R&D efforts at Fermilab are now under way to evaluate the possibility of even higher luminosities. Running at 10^{33} cm^{-2}s^{-1} or a constant 5×10^{32} cm^{-2}s^{-1} is considered possible, and might yield as much as 10 fb^{-1} per year.

In a year of LHC running at $10^{32} - 10^{33}$cm^{-2}s^{-1}, $t\bar{t}$ samples will be 1-2 orders of magnitude larger than those with 2 fb^{-1} at the Tevatron. With such samples, many LHC measurements will be limited by systematic effects which are difficult to quantify at this point. Nevertheless, improvements by a factor of 2-3 in the top mass uncertainty, and at least that much in sensitivity to rare decays and non-standard charged current couplings seem reasonable expectations. While Tevatron running should produce the best measure of V$_{tb}$, the first observation of $t \rightarrow Ws$ may come from LHC. If new physics does show up in top production or decays, then LHC is in an excellent position to either discover it, or study it if it should be found first at Fermilab.

11   Acknowledgements

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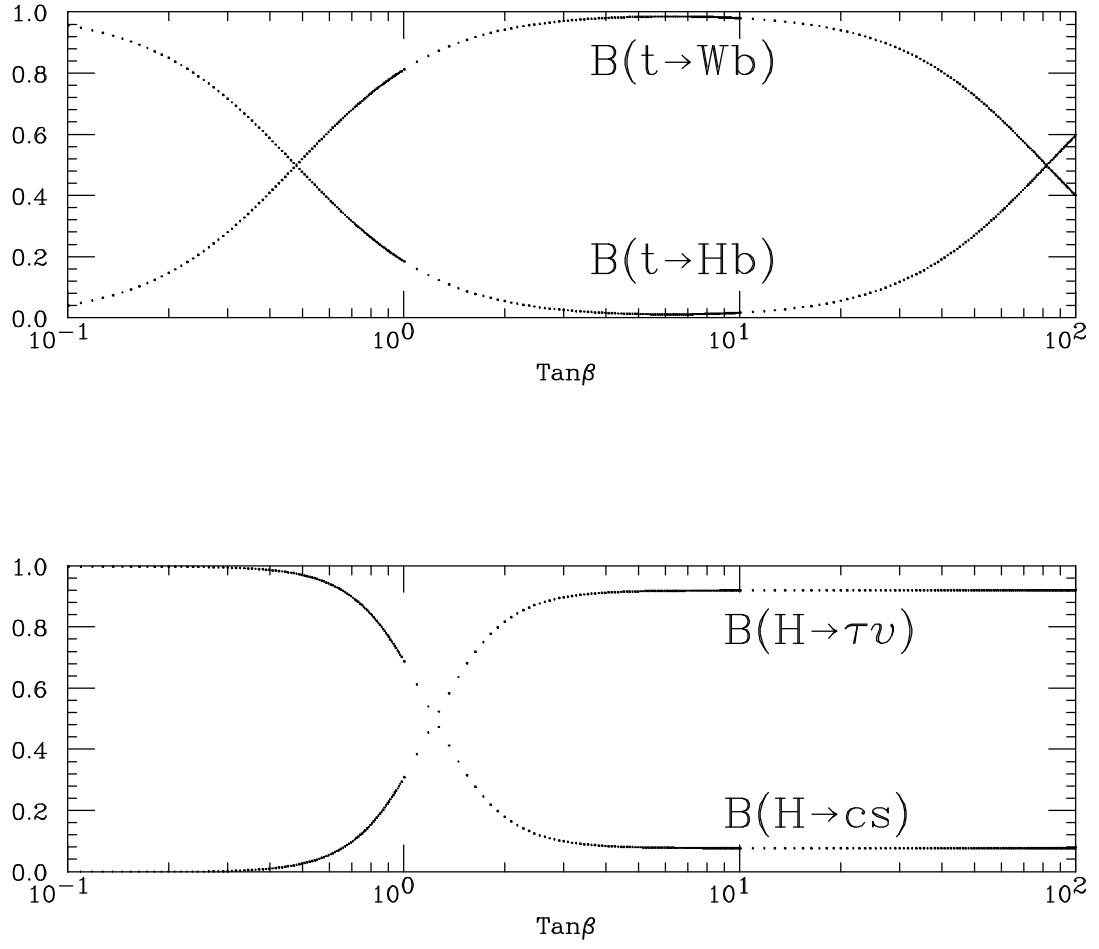
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Figure 1: Charged Higgs Branching Fraction for M_{top}=175 GeV/c^2 and M$_{Higgs}$=130 GeV/c^2.